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ScienceDirect
Procedia Engineering 10 (2011) 319–324
Engineering Procedia

ICM11

A Hybrid Approach To Determine Ductile Fracture Resistance

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Abstract

This article describes a hybrid approach to determine the ductile fracture resistance for laboratory specimens, combining both the numerically computed and experimentally measured load (*P*) versus load-line displacement (LLD) relationships for metallic fracture specimens. The hybrid approach employs the same principle as the conventional, multiple-specimen experimental method in determining the energy release rate. This method computes the *P*-LLD curves from multiple finite element (FE) models, each with a different crack depth. The experimental procedure measures the *P*-LLD curve from a standard fracture specimen with a growing crack. The intersections between the experimental *P*-LLD curve and the numerical *P*-LLD curves from multiple FE models dictate the LLD levels to compute the strain energy (*U*) using the area under the numerical *P*-LLD curves. This approach eliminates the requirement of using multiple fracture specimens and the requirement of measuring the compliance of the specimen via a multiple unloading procedure. In addition, this approach does not require the measurement of the crack-mouth opening displacement (CMOD). The validation procedure shows very accurate prediction of the J-Δa resistance curve for SE(B) specimens under mode I loading.

Selection and peer-review under responsibility of ICM11

Keywords: Load-line displacement; *J-R* curve; fracture resistance; hybrid approach.

Nomenclature

B	specimen width
B_N	net width of the specimen

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Selection and peer-review under responsibility of ICM11 doi:10.1016/j.proeng.2011.04.055

E	elastic modulus
J	elastic-plastic energy release rate
K_I	stress intensity factor
P	applied load
U	strain energy
S	span of the SE(B) specimen
W	width of a specimen
a_0	initial crack depth
a_i	current crack depth
b	remaining ligament length
σ_y	yield strength
σ_u	ultimate strength
Δ	load-line displacement
ν	Poisson's ratio

1. Introduction

The laboratory measurement of the fracture resistance curve, namely the *J-R* curve, often requires detailed instrumentation on the load-line displacement (LLD) and the crack-mouth opening displacement (CMOD) near the fatigue pre-cracked notch under multiple load cycles, as outlined in the testing standard [1,2]. The experimental J-Δa relationship then derives from the measured slopes of the LLD versus the applied load curve or the CMOD versus the applied load curve. For very ductile materials, the physical capacity of the CMOD gauge (the clip gauge) restricts the measurable fracture resistance curve to a very small amount of crack extension, hardly overcoming the blunting effect of the crack tip. The measurement of the mode I fracture resistance for very ductile metals requires a simplified and accurate approach based on the readily measurable quantities from the experiment.

This study aims to provide a hybrid, numerical and experimental approach to derive the material fracture resistance based on the readily measurable load versus LLD relationship for a fracture specimen under mode I loading. The fracture resistance, measured by the J-value, derives from the variation of the strain energy with respect to the change in the crack depth, computed from multiple finite element (FE) models with the same configuration but different crack depths. The comparison of the fracture resistance data obtained using the proposed approach with those reported for mode I single-edge-notched bend, SE(B) specimens confirms the accuracy of the proposed hybrid approach.

2. The hybrid approach

The fundamental idea of the proposed hybrid approach originates from the very first experimental approach to determine the energy release rate proposed by Begley and Landes [3]. The proposed hybrid approach combines the experimental P-Δ curve for a specimen with a growing crack and the P-Δ curves computed from multiple FE models with different stationary cracks. Figure 1 illustrates schematically the proposed hybrid approach to determine the fracture resistance using a single experimental specimen and multiple finite element models. The experimental part of the hybrid approach produces the P-Δ curve for a fracture specimen with a growing crack, while the numerical part of the hybrid approach generates a series of P-Δ curves from large-deformation, elastic-plastic analyses of multiple FE specimens with the same geometry, dimension and material, but different crack sizes.

Figure 1a sketches the single P-Δ curve obtained from the experimental specimen with the crack size a_0 and those obtained from the FE models with crack sizes a_1 to a_n. The intersection point between the experimental P-Δ curve and the numerical P-Δ curve defines a common loading and displacement level in the FE specimen with a stationary crack and the experimental specimen with a growing crack. Disregarding the experimental uncertainties, the extended crack size in the experimental specimen assumes theoretically the same size as the crack in the corresponding FE specimen, at this intersection point. Since the crack size in the FE model equals the current crack size in the experimental specimen, the energy release rate calculated from the multiple FE specimens, using the same approach as the conventional multiple-specimen experimental approach, represents the J-value in the experimental specimen with the corresponding crack size.

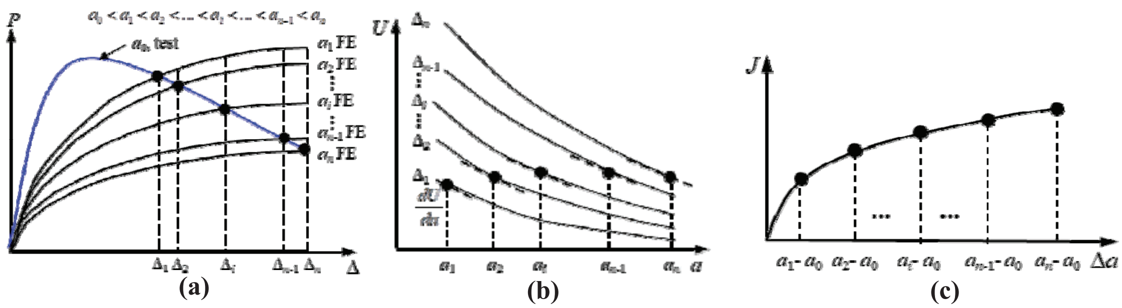


Fig. 1. Schematic description of the proposed hybrid method to determine the ductile fracture resistance.

The LLDs corresponding to the intersection points between the experimental curve and the numerical curves, *i.e.*, Δ_1 to Δ_n in Fig. 1a, define the displacement levels to compute the strain energy U for each crack depth. Figure 1b illustrates the schematic variation of the strain energy with respect to the crack depth, calculated from multiple FE models. To facilitate the calculation of the energy release rate from the FE models, the hybrid approach utilizes a regression analysis to derive approximate polynomial functions in terms of the crack size, a, to describe the strain energy curves shown in Fig. 1b.

The solid circles in Fig. 1b indicate the displacement level where the energy release rate calculated from multiple FE models equals (theoretically) the energy release rate in the experimental fracture specimen with a growing crack. The energy release rate at these solid circles computes from Eq. (1),

$$J = -(1/B)\,dU/da \tag{1}$$

Figure 1c sketches the J-values calculated at these solid circles with respect to the corresponding crack extensions.

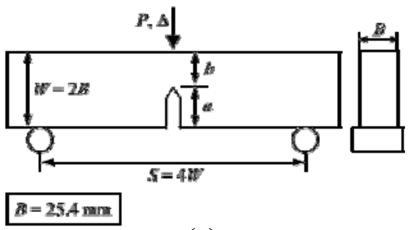
3. Validation

This section describes the validation of the proposed hybrid approach on single-edge-notched specimens under mode I three-point bending based on the experimental results reported by Zhu and Joyce

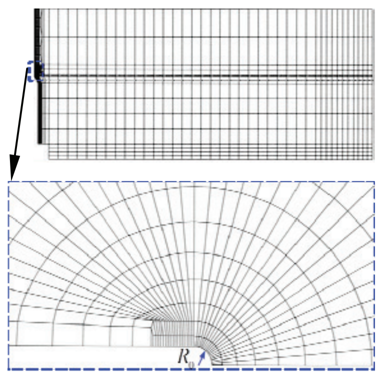
[4, 5] for HY80 steels. The HY80 steel has a Young's modulus E of 207 GPa, with a Poisson's ratio υ of 0.3. The yield strength, σ_y, of the HY80 steel equals 630 MPa, and the ultimate strength, σ_u, 735 MPa. The SE(B) specimen used by Zhu and Joyce [4] has a total thickness of B = 25.4 mm, with the net-thickness after side-grooving equal to 80% of the total thickness, or $B_N = 0.8B$.

Figure 2a sketches the geometry of the SE(B) specimen. The width of the specimen, W, equals to 50.8 mm, while the span over width, S/W, has a constant value of 4 for all specimens considered. The initial crack depth over the width ratio, a_0/W, equals 0.186 and 0.549 for the specimens selected in the current study. The SE(B) specimen with a relatively shallow crack depth (a_0/W = 0.186) represents a fracture specimen with low crack-front constraints, while the deep crack (a_0/W = 0.549) corresponds to a high crack-front constraint condition complying with the ASTM E-1820 requirement.

Figure 2b shows the typical, half finite element model for the mode I SE(B) specimens, built from 3-D 8-node brick elements. The FE model consists of one-layer of elements in the thickness direction, with all nodes in the FE model constrained against the out-of-plane displacement to represent the plane-strain condition. The presence of a plane of symmetry enables a half model, with the displacement degree of freedom for all nodes on the plane of symmetry constrained in the direction normal to that plane. The crack-tip contains a focused mesh with an initial root radius of 25.4 μm to facilitate numerical convergence under large deformation, as shown in Fig. 2b. The total number of nodes in the FE models with different crack depths varies from 2400 to 3400, with the number of elements ranging from 1100 to 1600. The numerical computation in this study utilizes the finite element research code, WARP3D [6].



(a)



(b)

Fig. 2. (a) Geometry of the SE(B) specimen; and (b) a typical FE mesh for the SE(B) specimen.

Zhu and Joyce [4] derive the J-resistance values following the recommendations in ASTM E-1820 [1], which utilizes the area under the load versus load-line displacement curve in the unloading compliance procedure. At i^{th} unloading cycle, the energy release rate equals,

$$J_{(i)} = \left(K_{I(i)}\right)^2 \left(1-\upsilon^2\right) / E + J_{pl(i)} \tag{2}$$

where $K_{I(i)}$ denotes the linear-elastic mode I stress-intensity factor at i^{th} unloading cycle, while $J_{pl(i)}$ refers to the plastic component of the energy release rate, which computes from the area under load versus plastic LLD, as outlined in the ASTM E-1820, for SE(B) specimens with $a/W \geq 0.282$. For shallow cracks with $a/W < 0.282$, Sumpter [7] proposes the relationship between the energy release rate and the area under the load versus load-line displacement.

For the SE(B) specimen with the initial $a_0/W = 0.186$, the current study generates ten FE models with different crack depths to compute the strain energy at ten different crack extensions (Δa_i), as listed in

Table 1. For the relatively deep crack of $a_0/W = 0.549$, the validation procedure includes eight FE models with different crack lengths to represent eight different crack extensions (Δa_i), as shown in Table 1.

Figure 3a shows the load versus load-line displacement for the experimental specimen of $a_0/W = 0.186$ with a growing crack indicated by the discrete circular symbols. The continuous curves in Fig. 3a describe the load versus LLD relationships computed from ten FE models, each with a stationary crack depth of $a_0 + \Delta a_i$, where Δa_i corresponds to the values tabulated in Table 1. The FE models with an increasing crack depth demonstrate consistently lower load resistance, as illustrated in Fig. 3a. The experimental P-Δ curve intersects each of the numerical P-Δ curves at a single load-line displacement level Δ_i. The numerical procedure then computes the strain energy based on the area under each numerical P-Δ curve corresponding to every Δ_i value. Figure 3b plots the strain energy U with respect to the crack extension for each of the ten Δ_i values as discrete symbols. A regression analysis fits each of the U-Δa curve in Fig. 3b with a second-order polynomial, indicated by the continuous solid curves in Fig. 3b. The energy release rate, J, corresponding to each crack extension, Δa_i, thus derives from Eq. (1), using the first-order derivative of the fitted polynomial for the strain energy U (at the corresponding Δ_i) with respect to the crack depth. Figure 3c elucidates the accuracy of the hybrid approach in computing the fracture resistance for specimens under mode I loading, evidenced by the close agreement between the J-Δa curve recorded in the experiment and that calculated using the above hybrid procedure.

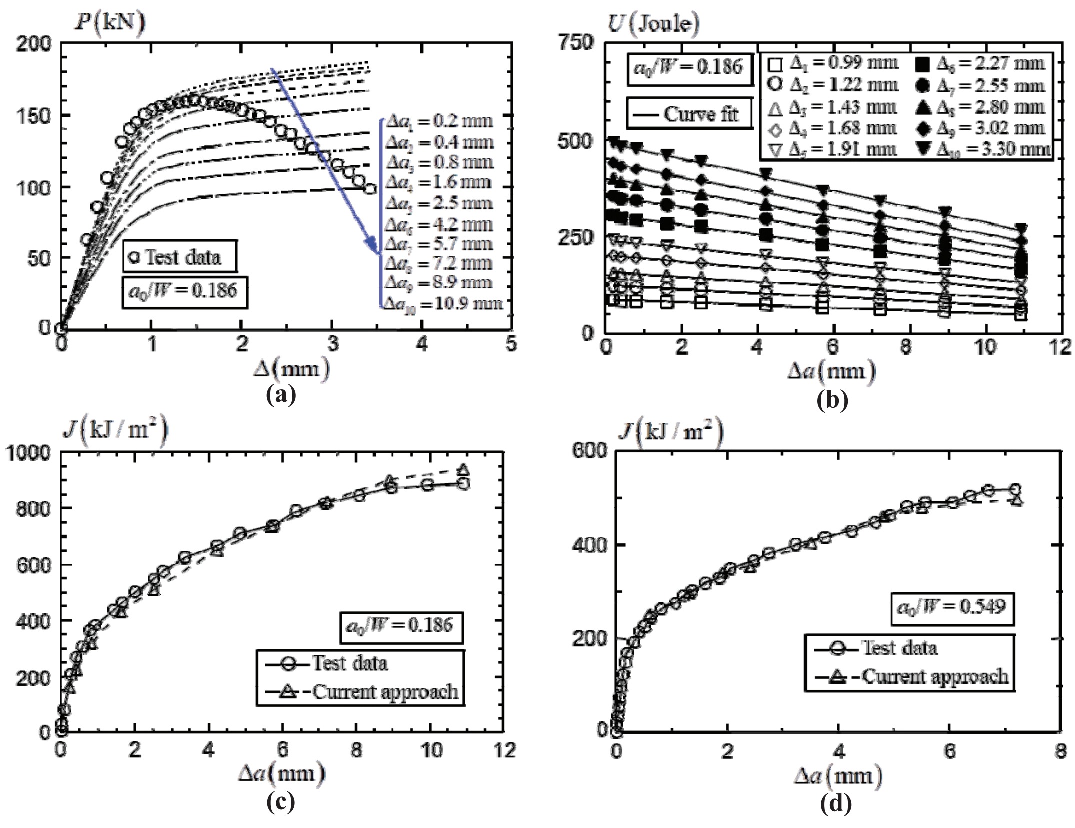


Fig. 3.(a) P-Δ curves for SE(B) specimen with $a_0/W = 0.186$; (b) strain energy U versus crack extension for $a_0/W = 0.186$; (c) comparison of the J-R curve in the test and that from the hybrid approach for $a_0/W = 0.186$; and (d) comparison of the J-R curve in the test and that from the hybrid approach for $a_0/W = 0.549$.

Table 1: The crack size in the multiple FE models for the two mode I SE(B) specimen.

a_0/W	a_0 (mm)	Crack extensions (mm)									
		Δa_1	Δa_2	Δa_3	Δa_4	Δa_5	Δa_6	Δa_7	Δa_8	Δa_9	Δa_{10}
0.186	9.4	0.2	0.4	0.8	1.6	2.5	4.2	5.7	7.2	8.9	10.9
0.549	27.9	0.6	1.3	1.9	2.4	3.5	4.8	5.5	7.1	-	-

Figure 3d demonstrates the close agreement between the experimentally measured *J-R* curve and the *J-R* curve obtained from the current hybrid approach, confirming the applicability of the hybrid method for fracture specimens under mode I loading, for a SE(B) specimen with a relatively deeper, initial crack, $a_0/W = 0.549$.

4. Summary and Conclusion

The proposed hybrid method predicates theoretically on the conventional multiple-specimen experimental approach in deriving the fracture resistance of a material. Instead of using multiple experimental specimens, the proposed approach employs an experimental fracture specimen and multiple FE models with varying crack sizes. The adoption of multiple FE models ensures strictly a non-growing crack in each of the FE model, which complies with the fundamental assumption in the conventional multiple-specimen experimental approach. The hybrid method provides a convenient and reliable approach in deriving the fracture resistance measured from fracture specimens under mode I loading. The predicted J-R curve using the hybrid approach follows closely the experimental measurement.

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